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# Teleseisms monitoring using chirped-pulse φOTDR

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## ABSTRACT

Monitoring of seismic activity around the word is a topic of high interest for the analysis and understanding of deep Earth dynamics. However, the deployment of a homogeneous network of seismic stations both onshore and offshore poses a strong economic challenge that makes this solution practically inviable. Using the pre-existing fiber optical network for seismic monitoring arises as an excellent solution with important advantages in terms of ubiquity and cost. In this communication, we present the detection of an M8.2 earthquake occurred in Fiji Island using distributed acoustic sensing based on chirped-pulse φOTDR. Two sensors were placed simultaneously at two different locations at >9,000 km from the earthquake epicenter: a metropolitan area and a submarine environment. The recorded data is post-processed using a 2D linear filter to cancel out environmental noise. The resulting signals are compared with the signals acquired by nearby seismometers. The attained good matching between the recorded data and the seismometer data shows the strong potential of the use of the already-deployed communication fiber network for teleseism monitoring.

**Keywords:** Rayleigh scattering, optical time-domain reflectometry, seismology, distributed sensing

## 1. INTRODUCTION

Nowadays, a vast array of optical fiber is deployed around the word, with more than 1 million kilometers of optical fiber distributed mainland and across the oceans. This fiber network has been continuously growing over the last few decades, being used primarily for telecommunication purposes. During that time, numerous advances have taken place in optical components and systems. A developing field of particular interest for their manifold applications is that of distributed optical fiber sensing. Distributed fiber sensors employ a conventional optical fiber as a dense array of punctual optical sensors able to measure certain physical magnitudes that affect the fiber refractive index, such as strain, temperature or birefringence. This technology is based on scattering processes occurring in the fiber, and depending of which process is exploited (e.g., Rayleigh, Brillouin or Raman), the resulting sensors will have particular features[1-3]. The low number of trace averaging needed in sensors based on Rayleigh scattering have made this technique useful for measuring at acoustic frequencies, giving rise to the field of distributed acoustic sensing (DAS).

DAS have been recently proposed for distributed sensing of seismic activity around the Earth[4,5]. The fundamental goal is to re-purpose the deployed telecommunication fiber optic network for detecting and monitoring seismic activity for tomographic applications. Seismic tomography is a powerful tool for imaging the Earth structure by using earthquakes and other terrestrial wave sources. Currently, tomographic methods rely on the existing network of seismometers spread around the word. However, this network is quite inhomogeneous, mainly distributed onshore over North America, Europe and in certain regions of known strong seismic activity. Consequently, the sole use of this network results in the acquisition of biased and low spatially-sampled information. The deployment and maintenance of a homogeneous cluster of seismometers around the Earth results practically and economically inviable. Hence, the re-use of the telecommunication fiber network as distributed sensor for seismic monitoring arises as an excellent solution for seismic tomography.

Recently, a novel DAS based on phase-sensitive (φ)OTDR has been introduced, known as chirped-pulse φOTDR (CP-φOTDR)[6]. This system has proven capable of quantifying the magnitude of ongoing perturbations over the fiber with record sensitivities[7] for a distributed sensor, improved performance[8] and simpler setup[6] than traditional configurations requiring coherent detection (requiring polarization diversity and phase diversity)[9] or time-consuming laser frequency sweeping strategies[10]. Using CP-φOTDR, we have detected an M8.2 earthquake occurred in Fiji Island last August, 2018

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from two different locations with very different environmental conditions and placed >9,000 km away from the earthquake epicenter. On the one hand, we have measured the earthquake from a densely populated metropolitan area in Pasadena, CA, USA. On the other hand, the earthquake was detected from a shallow submarine fiber in the city of Zeebrugge, Belgium. Such a different, noisy locations ensures a thorough analysis of the possibilities of the optical fiber to monitor teleseism activity. The results shown in this communication represent a firm step forward in the use of the telecommunication fiber optical network as distributed seismometers.

# 2. OPTICAL ARRANGEMENT FOR SEISMIC MONITORING

## 2.1 Chirped-pulse phase-sensitive OTDR

The distributed sensing method known as CP-φOTDR was introduced several years ago[6] as an alternative technique to quantify the detected perturbation with much simpler optical arrangement than existing methods to date[9,10]. Similar to classical φOTDR, a train of optical pulses is launched over a fiber and successive Rayleigh backscattered traces are compared in order to detect a perturbation. Whenever a strain or temperature perturbation affects the fiber, the central frequency of the propagating light is slightly shifted by an amount proportional to the perturbation. In CP-φOTDR, a sufficiently high linear chirp is induced into the input pulse, inducing a frequency-to-time mapping process. Thus, the directly-detected temporal trace suffers a time shift proportional to the frequency shift locally over the perturbation position. This modification in the φOTDR scheme entails important advantages, such as the simplicity in the employed setup, the robustness against laser phase noise and the record sensibilities achievable[6-8]. The employed optical setup of the fiber interrogator unit is represented in Fig. 1(a), in which a distributed amplification stage (namely, Raman amplification) has been added to increase its operating range[11].

## 2.2 Fiber distribution in Pasadena and Zeebrugge

Two interrogation units identical to the one described in the previous Section are placed in two different locations and connected to already-deployed fiber optic cables. In the city of Pasadena, we use a 25 km fiber that is part of the local telecommunication network. Its geometrical distribution is plotted in Fig. 1(b), together with a map of the real fiber distribution. In the inset of Fig. 1(b), we can observe that the fiber includes several loops that contribute to increase the length with respect to the geometrical distance occupied by the fiber. In this location, the main source of noise comes from traffic and other human activity. In the city of Zeebrugge, we use a 40 km fiber deployed perpendicular to the shore, reaching almost 33 m of depth (see Fig. 1(c)). The fiber was deployed there to monitor a power cable from an offshore wind farm. Such a shallow fiber is highly exposed to superficial noise, as ocean waves or ship-induced noise.


Figure 1. (a) Setup of the CP-φOTDR employed for the experimental tests. ECL: External cavity laser, SG: Signal generator, SOA: semiconductor optical amplifier, FUT: fiber under test, IU: Interrogator unit. (b) Geometrical distribution of the fiber in Pasadena, including the location of the reference seismometer, the interrogator unit, and an inset with the real distribution of the fiber over the city. (c) Map of the fiber distribution in the cost of Zeebrugge, including the location of the seismometer (BOST), the interrogator unit, and an inset with the location of the fiber over the north shore of Europe.

# 3. EXPERIMENTAL RESULTS

The traces acquired by the interrogator unit from each of the launched pulses can be plotted forming a waterfall, in such a way they form a 2D image in which the abscissa represents measurement time (4200 s) and the ordinate represents fiber length. As the environment in the measurement locations is especially noisy, the raw acquired data must be processed to implement a denoising process. We have selected to use a simple 2D spation-temporal band-pass filter to isolate the spectral bands of the earthquake signal from the rest of the detected vibrations. In particular, by having previous knowledge of the typical spectral content of seismic activity, we have selected the transition bands of the filter at 0.02 Hz and 1 Hz for the temporal frequency axis and at 0 and $4 \cdot 10^{-4}$ $m^{-1}$ for the spatial frequency axis. Once the filter is applied, most of the background interference noise in the measurements is eliminated, and the remaining signal energy can be mostly associated to earthquake information. The resulting data is analyzed by comparing the filtered signal with the trace acquired by nearby seismometers (see Fig. 1(a) and (b)). For this purpose, we stack the traces of the last 5 km of fiber in each location. In Pasadena, the reason is that the last 5 km corresponds to fiber directed from West to East location, which coincides with the direction of propagation of the earthquake. Hence, the CP-φOTDR trace is compared with the seismometer trace in the West-East direction. In Zeebrugge, however, the main reason of taking the last 5 km of fiber is that they correspond with the deepest fiber, and therefore the background noise associated to surface waves is lower. In this case, the traces from the seismometers in the West-East and North-South directions are rotated to the fiber azimuth for comparison. In order to compare the arriving frequency components along the time, we compare the spectrograms of the CP-φOTDR stacked trace and the seismometers. The results are discussed in what follows.

### 3.1 Results from Pasadena

Figure 2 presents the comparison between the spectrograms of the filtered and stacked CP-φOTDR trace (Fig. 2(a)) and the seismometer trace (Fig. 2(b)). The difference in the earthquake starting time in both instruments is due to a delay in the beginning of the recordings. We can observe that the time-frequency dynamics is similar in both measurements. In particular, right at the beginning of the earthquake, higher frequencies (>1 Hz) arrive, corresponding to primary waves. After that, the maximum frequency components of the signal reduce along the time, finding some peaks associated to crust-reflected primary waves and secondary waves, respectively. The difference in the magnitude of the obtained data is due to the fact that CP-φOTDR measures fiber strain perturbations while the seismometers measure particle velocity. Even though these magnitudes are not directly comparable, they are almost proportional, allowing for a qualitative comparison.

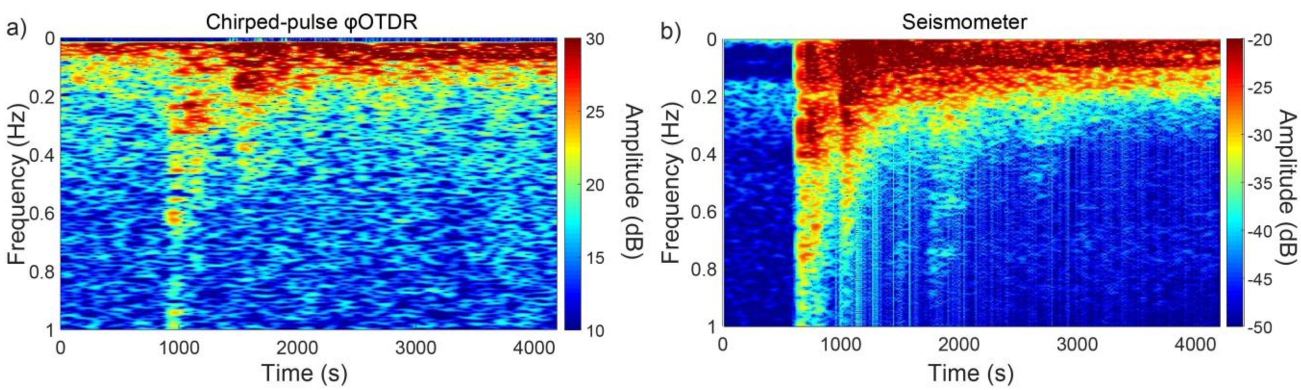


Figure 2. Results from Pasadena: spectrograms of the stacked CP-φOTDR trace (a) and the seismometer trace (b).

### 3.2 Results from Zeebrugge

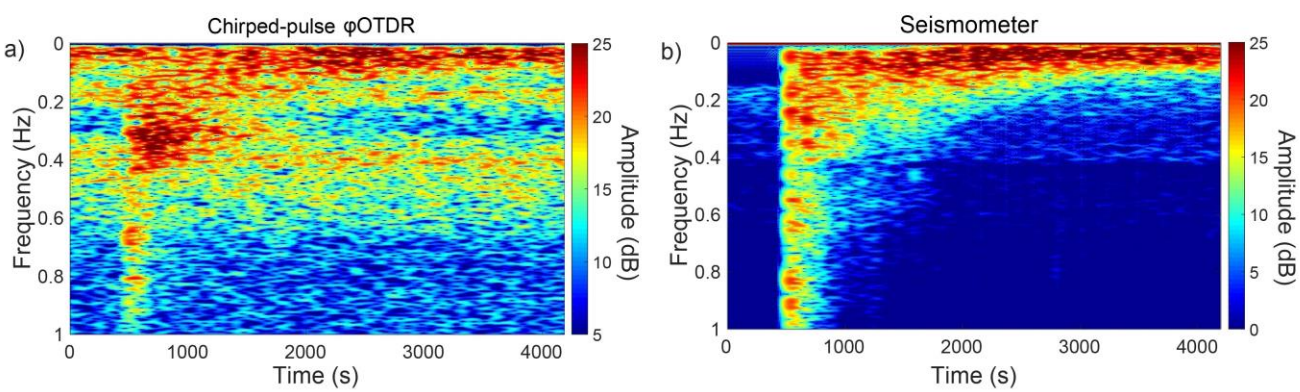


Figure 3. Results from Zeebrugge: spectrograms of the stacked CP-φOTDR trace (a) and the seismometer trace (b).

Figure 3(a) shows the spectrogram of the stacked traces acquired in Zeebrugge via CP-φOTDR, and Fig. 3(b) shows the seismometer trace. We can observe similar behavior than in the case of Pasadena. However, constant frequency components around 0.2 Hz and 0.4 Hz appear in the CP-φOTDR trace that are not related to the earthquake (those components do not appear in Fig. 3(b)). The component at 0.2 Hz corresponds to ocean waves and the one at 0.4 Hz is related to microseisms associated to the former ones. A deep analysis of these kind of waves is out of the scope of this communication. Still, it is possible to realize the strong potential of DAS for monitoring submarine seismic activity.

## 4. CONCLUSIONS

In this communication, we have demonstrated the viability of using the already-deployed telecommunication optical fiber network for the monitoring of seismic activity around the word. We have detected an M8.2 earthquake occurred in Fiji Island from two different locations with very distinctive environmental features. In spite of the great differences in terms of noise, we have performed a similar analysis in both cases, namely, the application of a linear 2D band-pass filter to a waterfall of CP-φOTDR traces. The resulted data is compared with data acquired by nearby seismometers, verifying the similarities in the obtained results. The presented results may give place to important developments in the field of seismic topography.

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